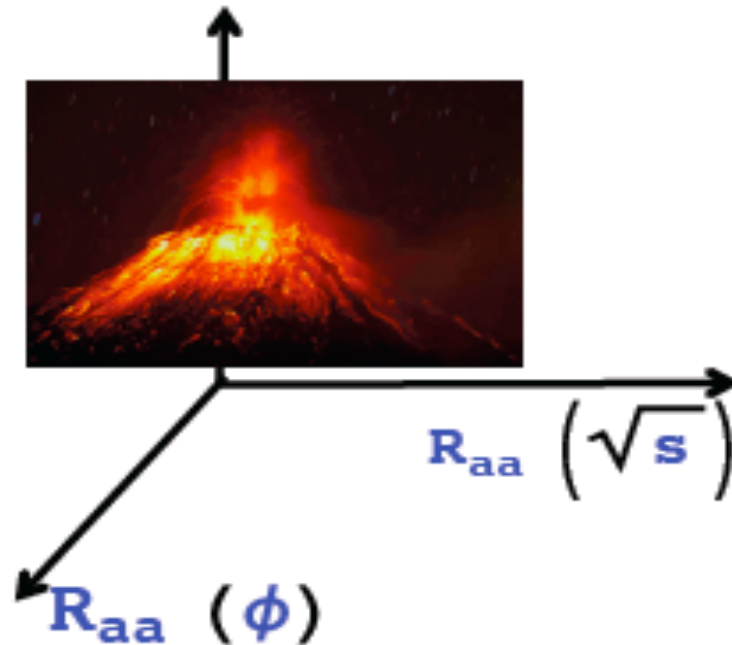


OPAQUENESS EVOLUTION AND HARD PROBE OF FLUCTUATING GEOMETRY FROM RHIC TO LHC



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

RIKEN BNL Research Center

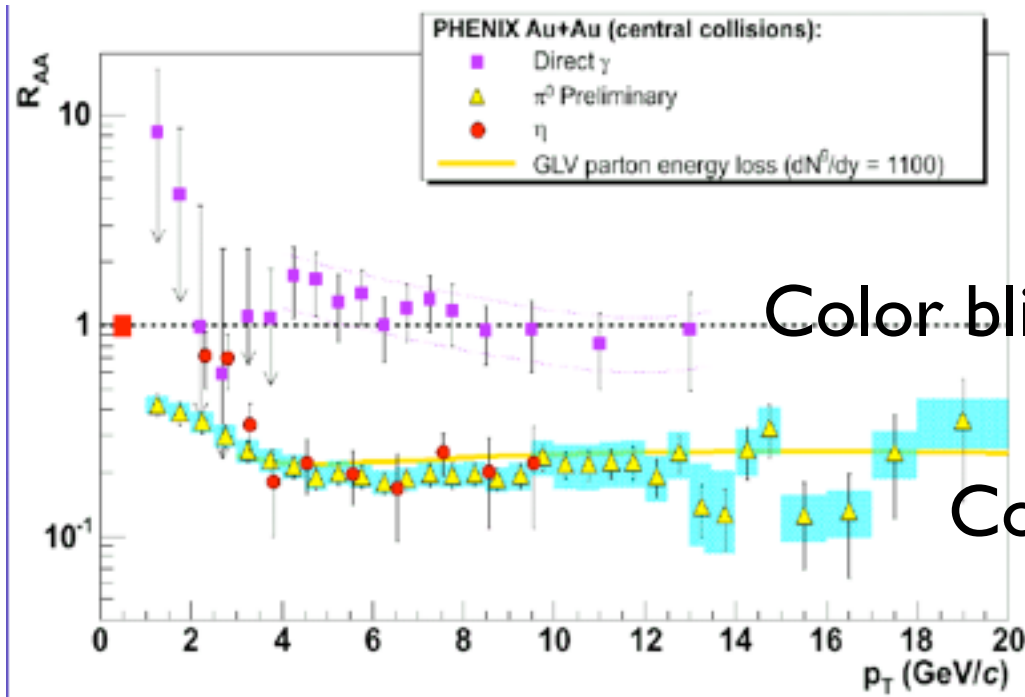


Outline

- Introduction: opaqueness evolution
- What we've learned from the geometry of jet quenching with RHIC+LHC data?
- Opaqueness evolution from “one more dimension”
- Summary & Discussions
 - Harmonic tomography & hard-soft dihadron corr.
 - Could there be jet quenching in the “mini-bang”?

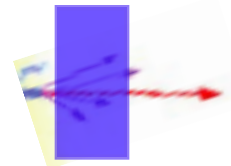
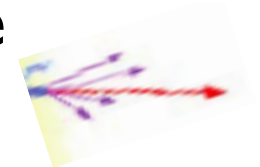
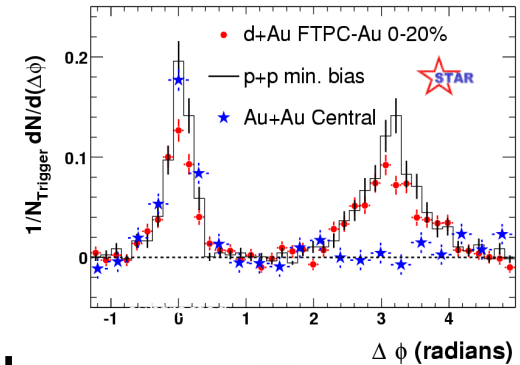
*X. Zhang, JL, arXiv:1311.5463, 1208.6361 (PRC),
1210.1245 (PRC), 1202.1047 (PLB);
D. Li, JL, M. Huang, arXiv:1401.2035;
JL, arXiv:1109.0271;
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302*

A Color-Opaque Plasma



Color blind probe

Colorful probe



A qualitatively different medium

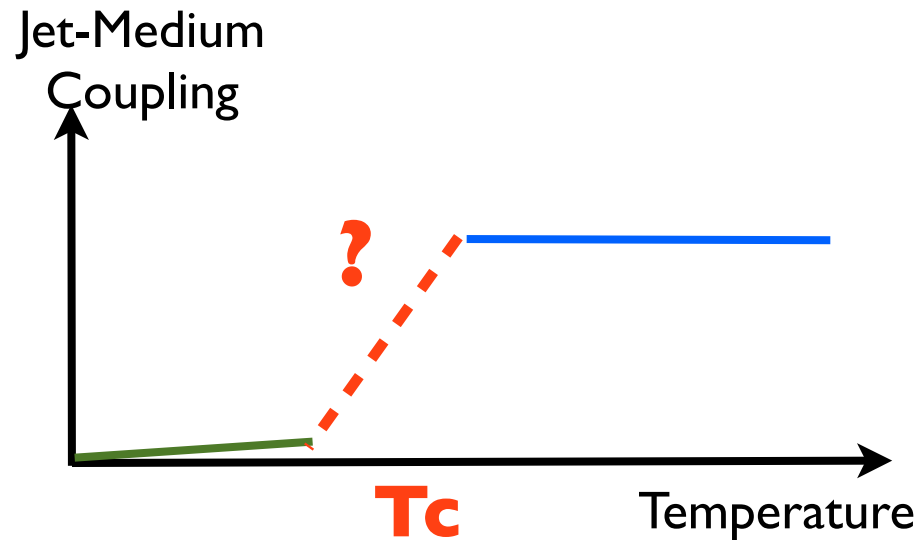
Jet-Medium
Coupling

**Zero/Low
(Confined)**

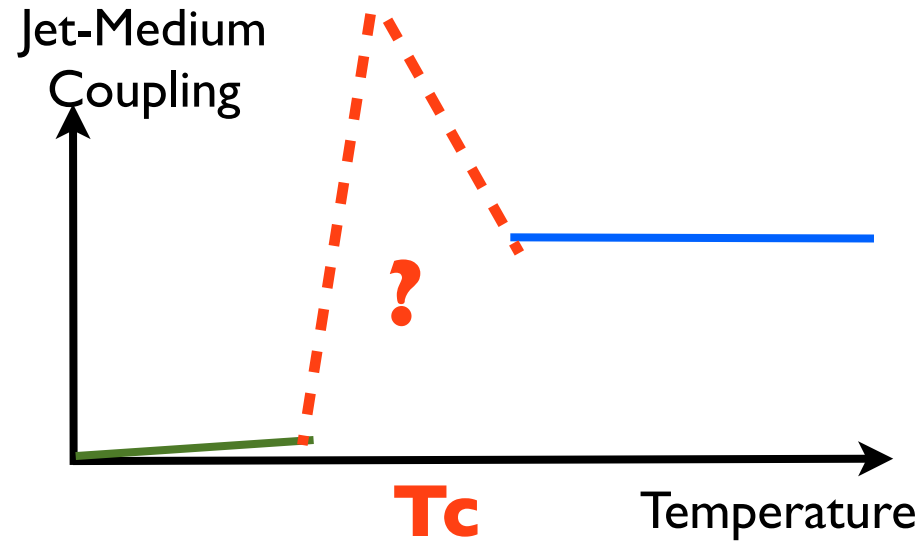
High (liberated)

Temperature

From Transparency to Opaqueness



“Waterfall” scenario

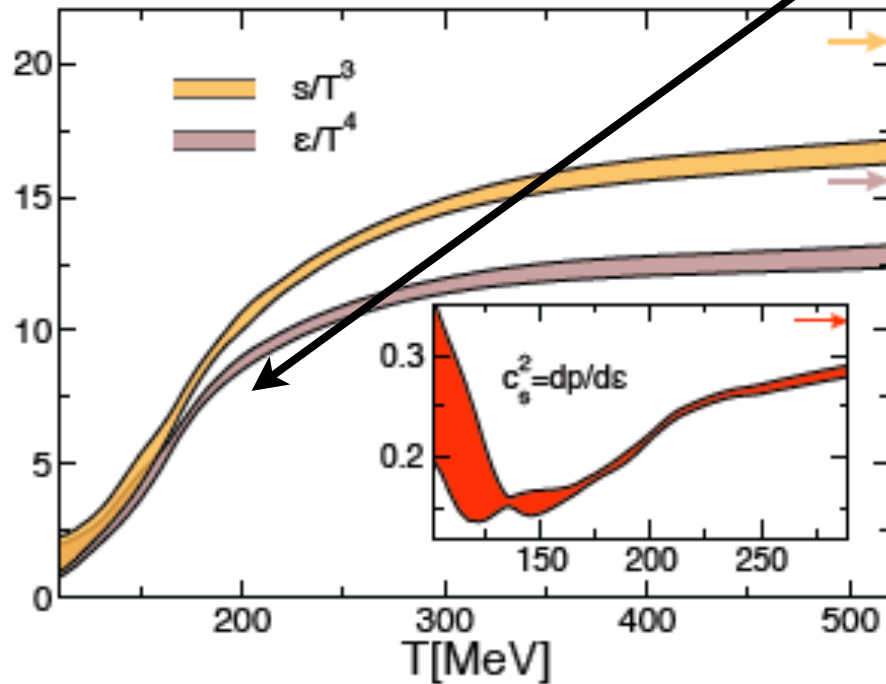


“Volcano” scenario



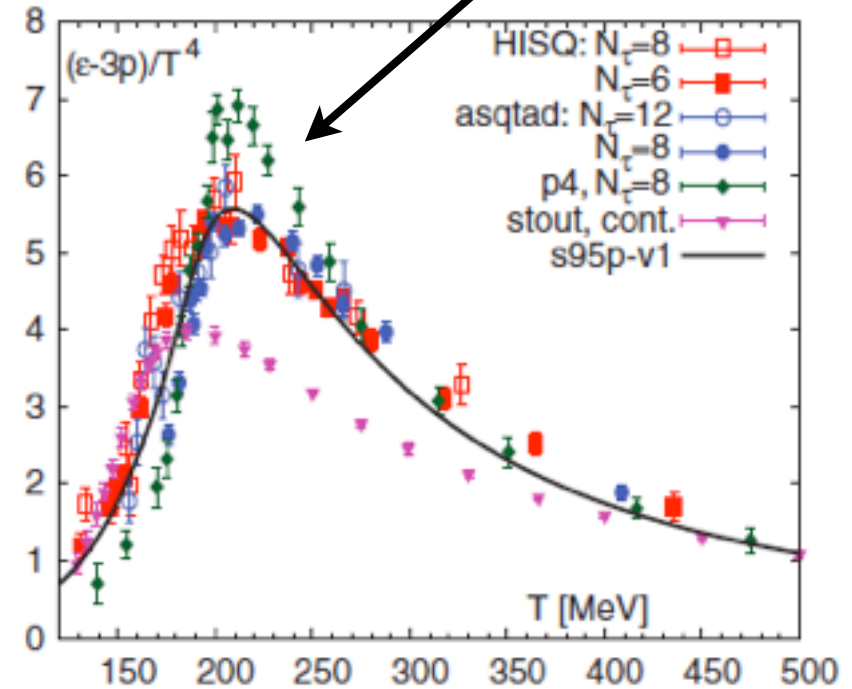
To me, this is a question of fundamental interest, and one we must answer for understanding of jet-quenching & of the medium itself.

Hot off the Lattice: Crossover, but Rapid



“Rapid Up” or “Rapid Down”:

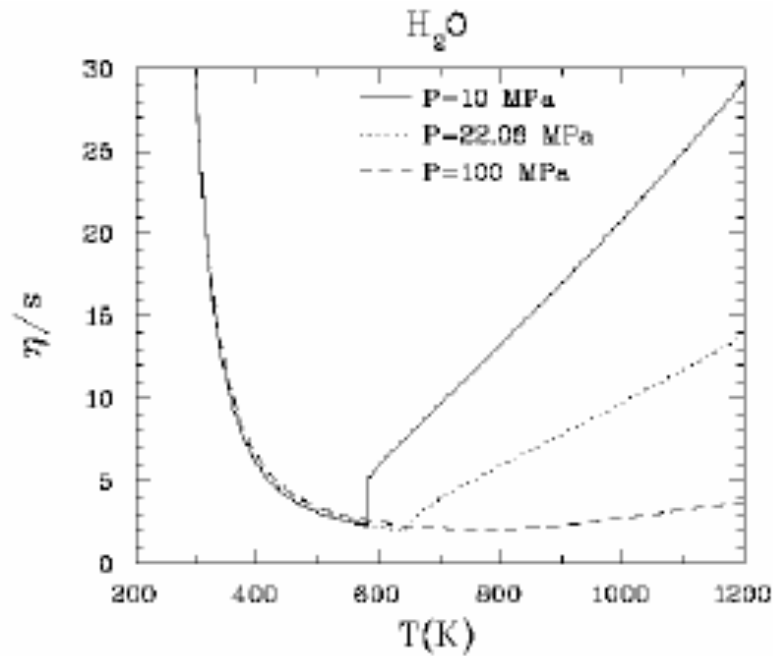
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/ \bar{Q} - Q free energy/...



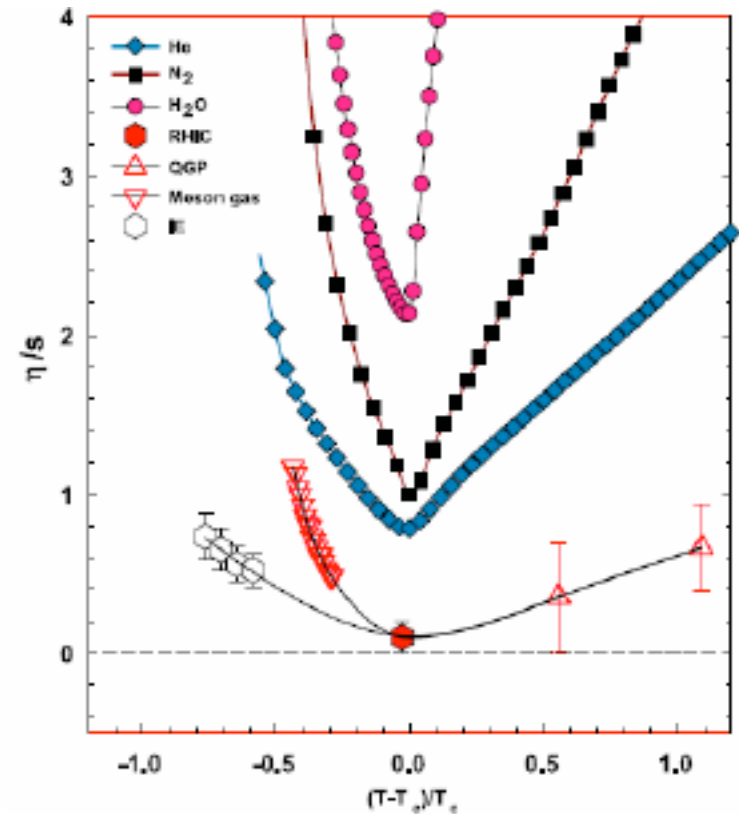
“Peak” or “Dip”:

trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
 \bar{Q} - Q internal energy/
speed of sound/...

How about the “Perfect-ness” of Fluid?



**Csernai, Kapusta, McLerran,
PRL(2006)**



Lacey, et al, PRL(2007)



V.S.



How can we get the answer?

Do we even have a chance
to find out the answer?

Luckily, we seem to be able to:

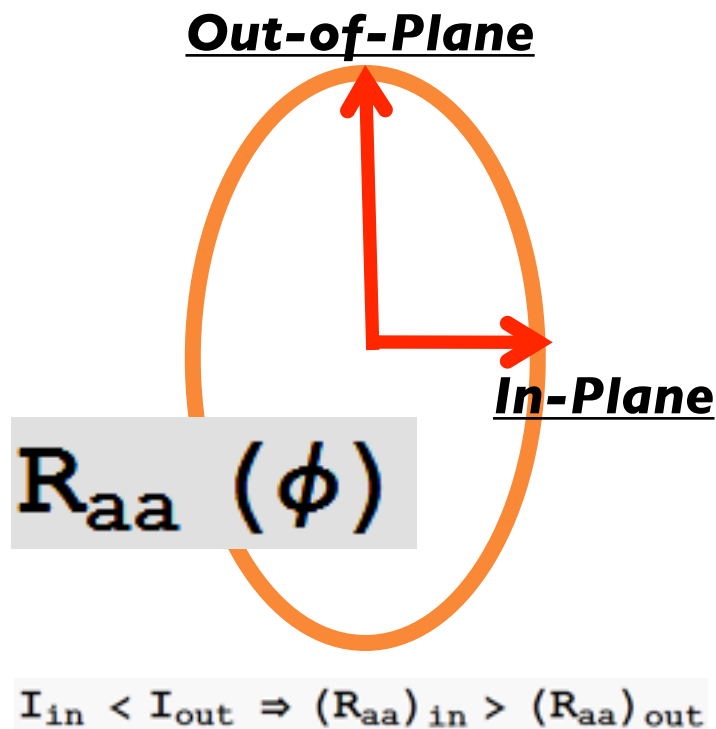
Geometry ; evolution RHIC --> LHC

Geometric Anisotropy of Jet Quenching

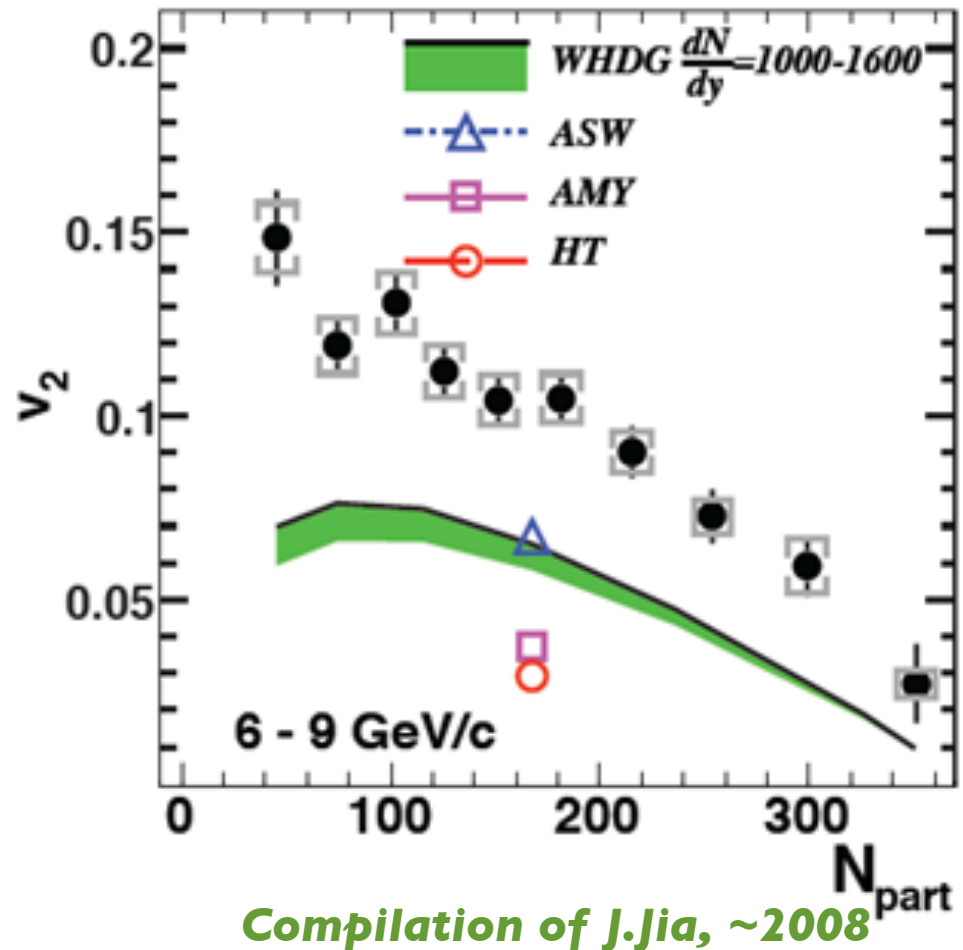
Geometric tomography (~2001): Gyulassy, Vitev, Wang, ...

Geometric limit of high-pt v_2 : Shuryak; Drees, Feng, Jia; ...

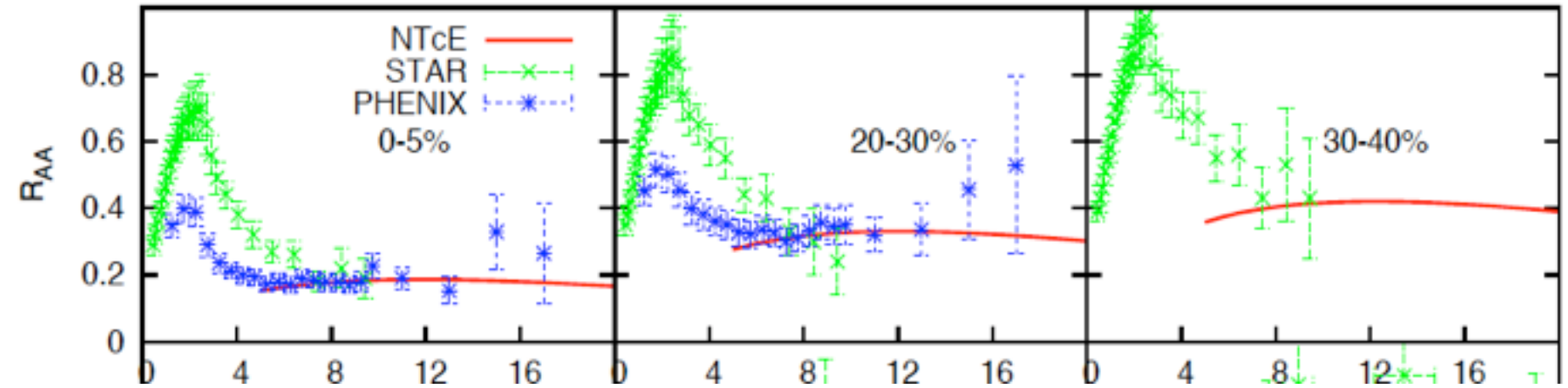
Till ~2008: clear discrepancy between data / any model



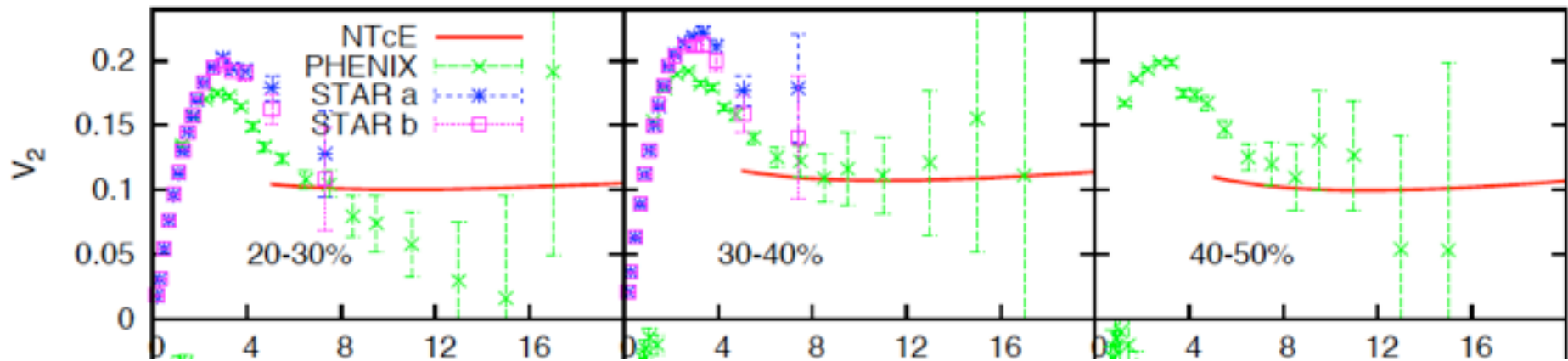
Positive v_2 for high Pt hadrons



Differential Data at RHIC

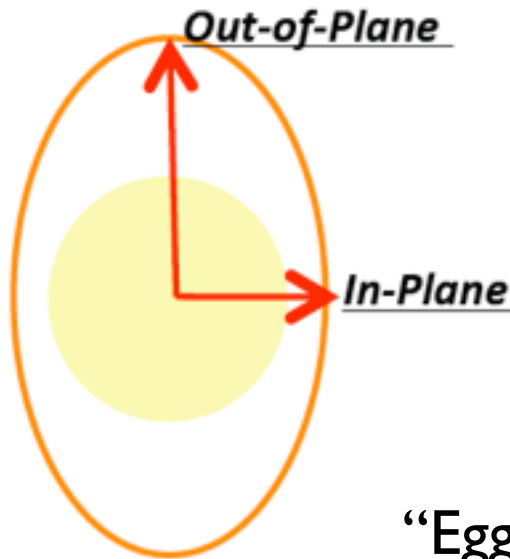


$$R_{AA}(\phi) = R_{AA}[1 + 2V_2 + \dots]$$



Adapted from Zhang & JL, arXiv: 1311.5463

Where Are Jets Quenched (More Strongly)?



**Taken for granted in all previous models:
“waterfall” scenario.**

**We realized the puzzle may concern
more radical questions:**

Where are jets quenched (more strongly)?

Geometry is a sensitive feature:
“Egg yolk” has one geometry, “Egg white” has another.

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

Jinfeng Liao^{1,2,*} and Edward Shuryak^{1,†}

¹*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*

²*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

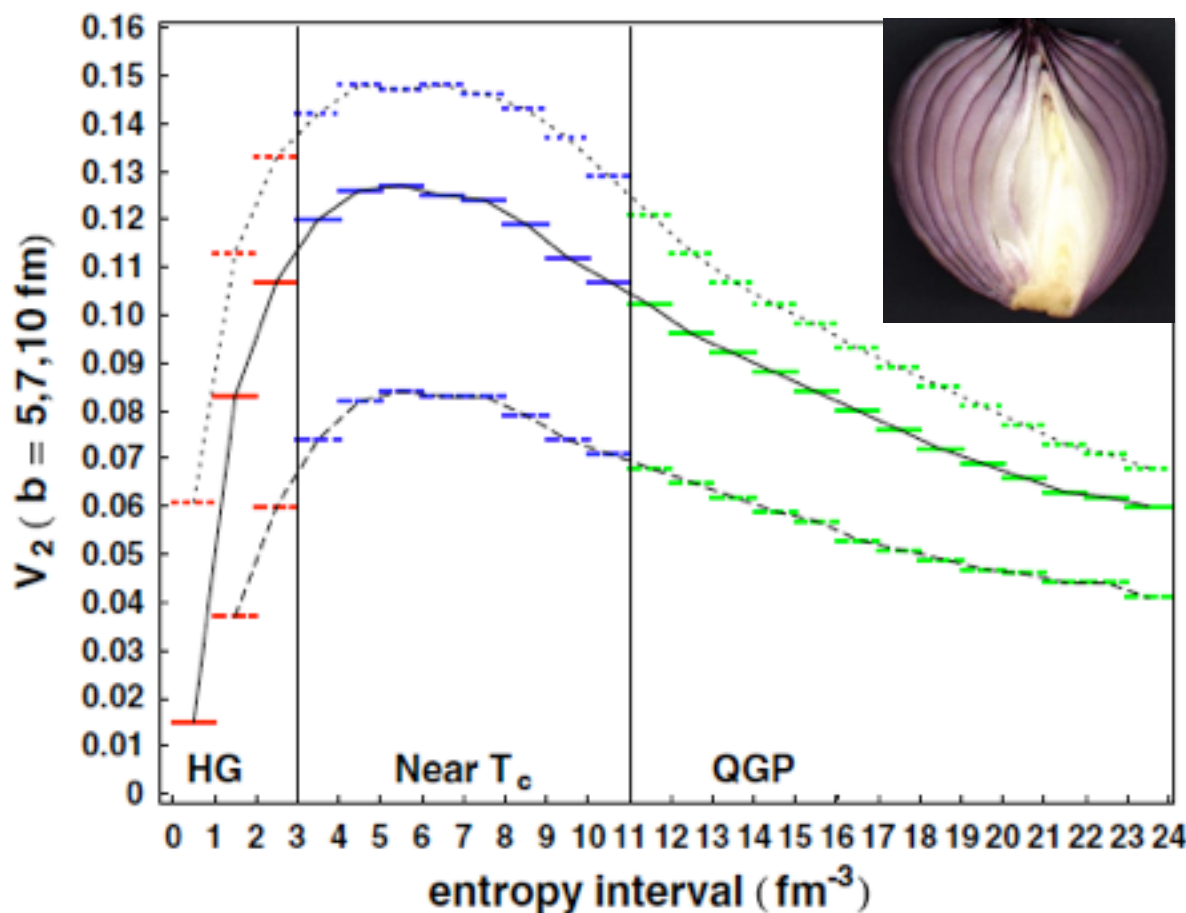
Layer-wise Jet Quenching

$$f_P = \exp \left\{ - \int_P \kappa[s(l)] s(l) l^m dl \right\}$$

$$R_{AA}(\phi) = \langle (f_P)^{n-2} \rangle_{P(\phi)}$$

scan the jet quenching geometry
layer by layer in density

$$\kappa[s] = \kappa_c * \theta[s - s_a] * \theta[s_b - s]$$



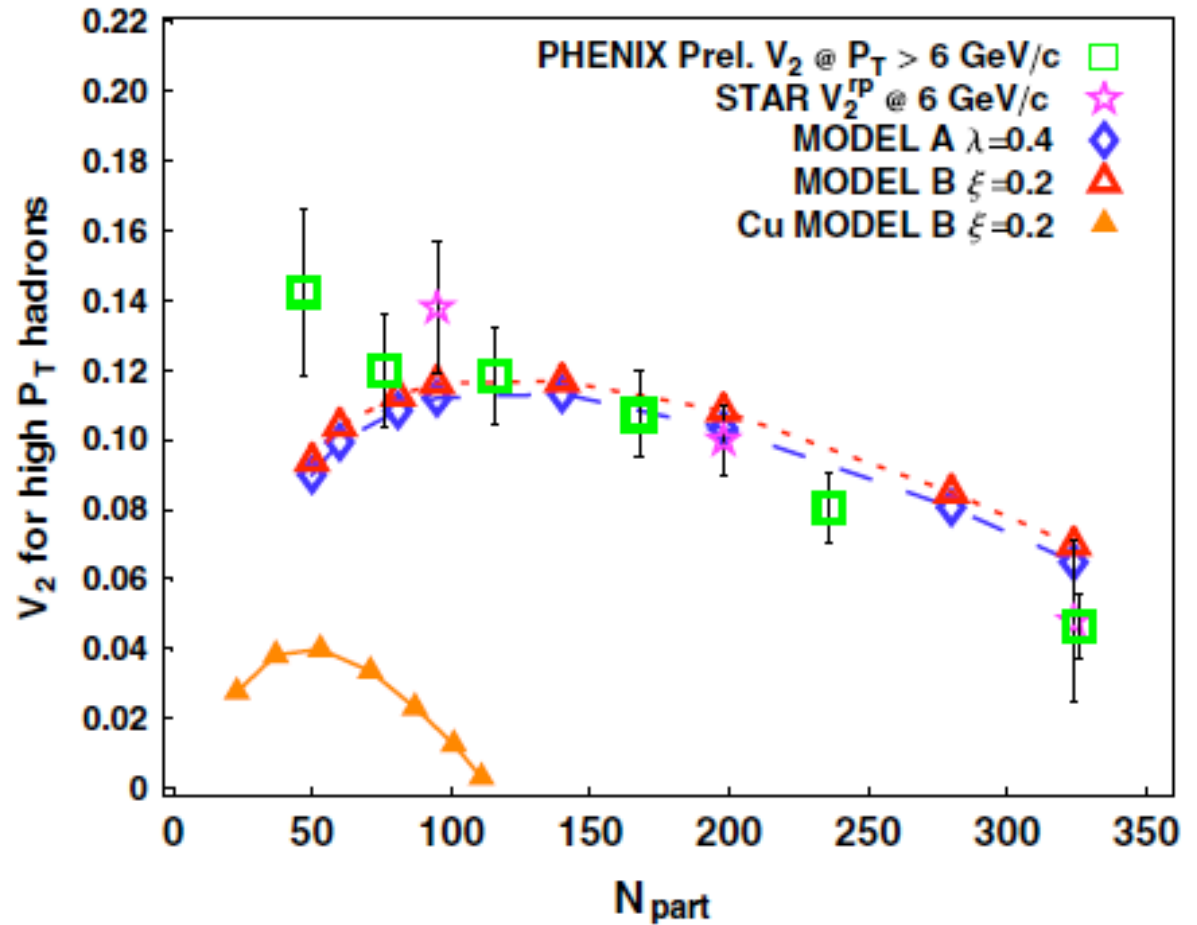
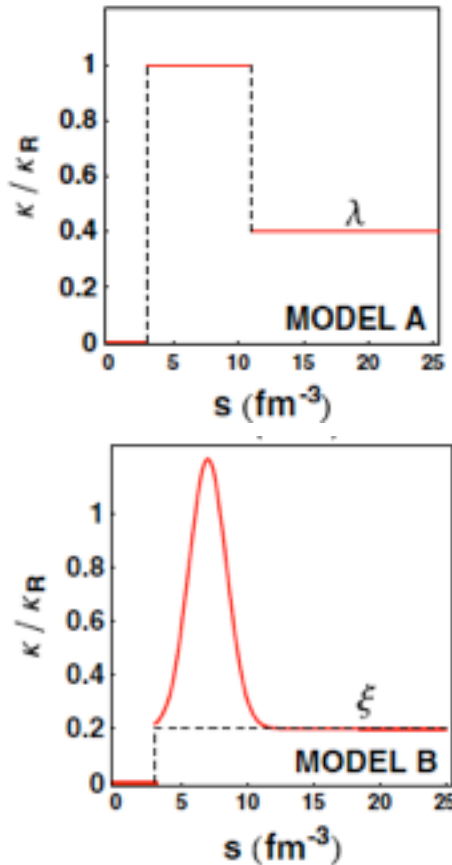
Assume jet quenching
occurs only in a
specific density interval
with constraint from
overall R_{AA}

-->

look at v_2 from that layer:

**Near- T_c layers
give the
strongest anisotropy!**

Near-Tc Enhancement (NTcE)



In the paper PRL(2009) we concluded:
 “In relativistic heavy ion collisions the jets are quenched
 about **2--5 times stronger** in the near-Tc region
 than the higher-T QGP phase.”

NTcE as a Generic Mechanism

Near Tc Enhancement (the “volcano”) generically increases the contribution to jet quenching from later stage and outer layer of the fireball, and gives **more anisotropy**.

- * relatively insensitive to detailed shape of “volcano”
- * works in jet quenching modelings with varied implementations (e.g. geometric models, or GLV/WHDG/CUJET, or ASW, with/without fluctuations/transverse expansions)

Francesco-Di Toro-Greco

Renk-Holopainen-Heinz-Shen

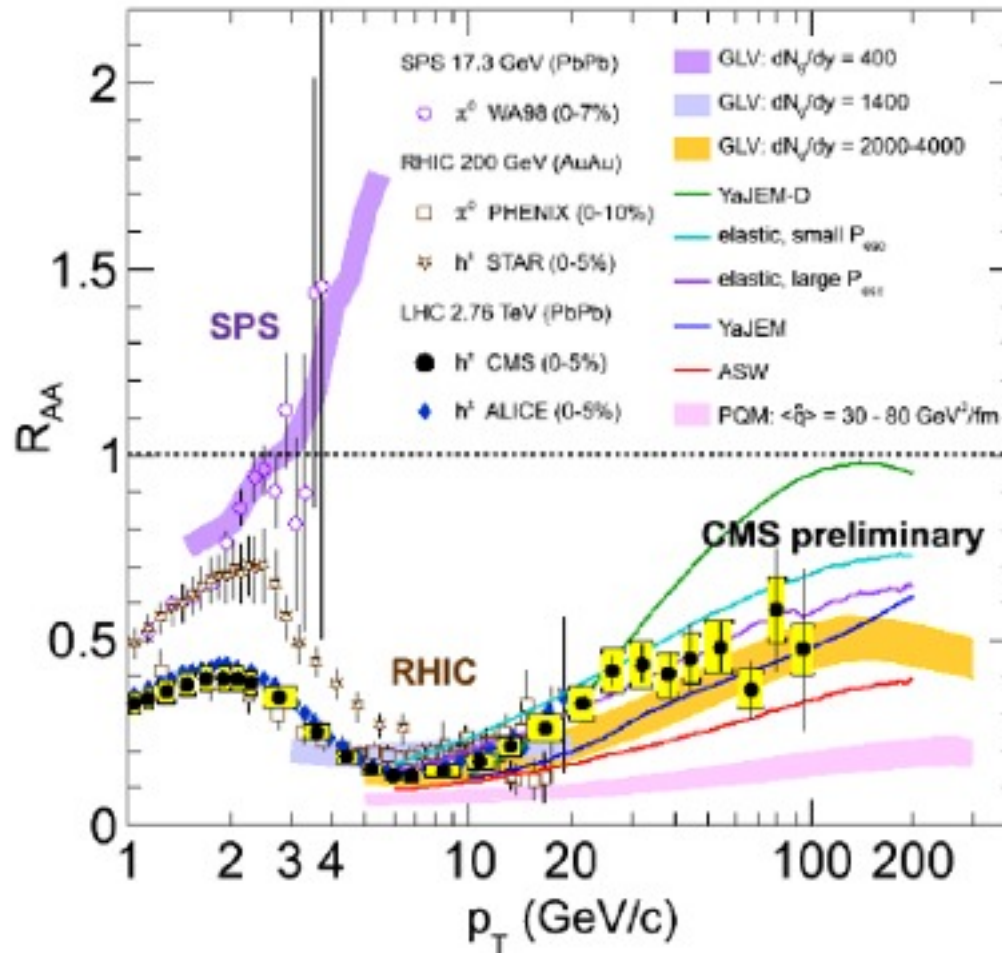
Gyulassy, Buzzatti, Bezt

Fries & students

Marquet & Renk

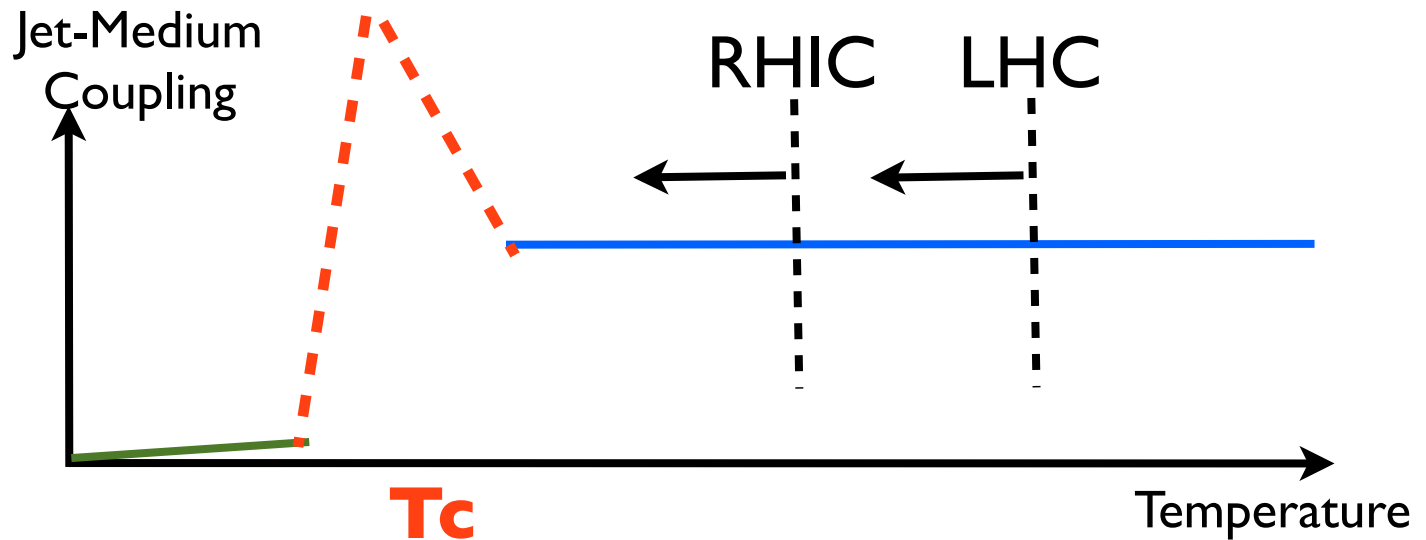
Jia & Wei

The RHIC+LHC Era



Beautiful jet quenching measurements from
ALICE, ATLAS, CMS

NTcE: Shift to Less Opaque Medium at LHC



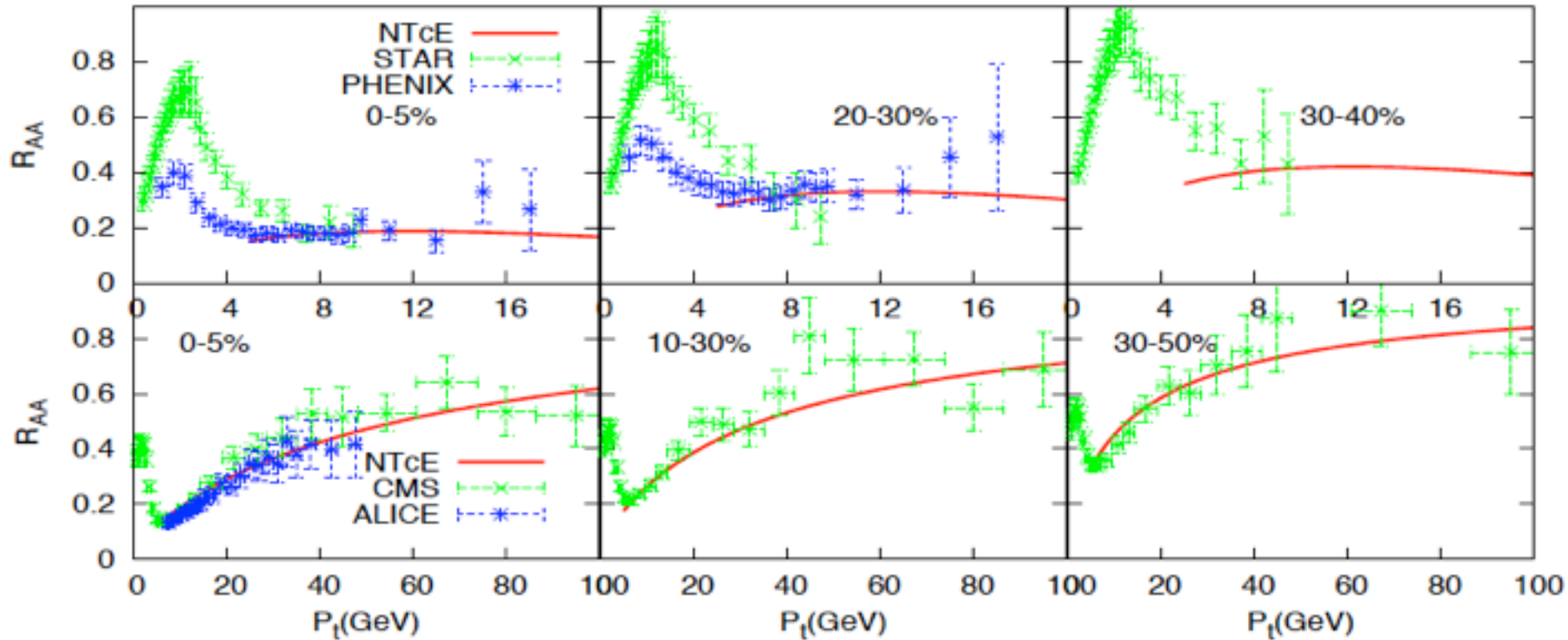
LHC compared with RHIC:

- * high T QGP occupies more space-time evolution
- * the near- T_c will weigh less, with “volcano” effect reduced

-->

- * Naturally predicts a less opaque (on average) medium seen by jets (note however density doubles)
- * Anisotropy from the “volcano” and “waterfall” scenarios will become closer

Raa from RHIC to LHC



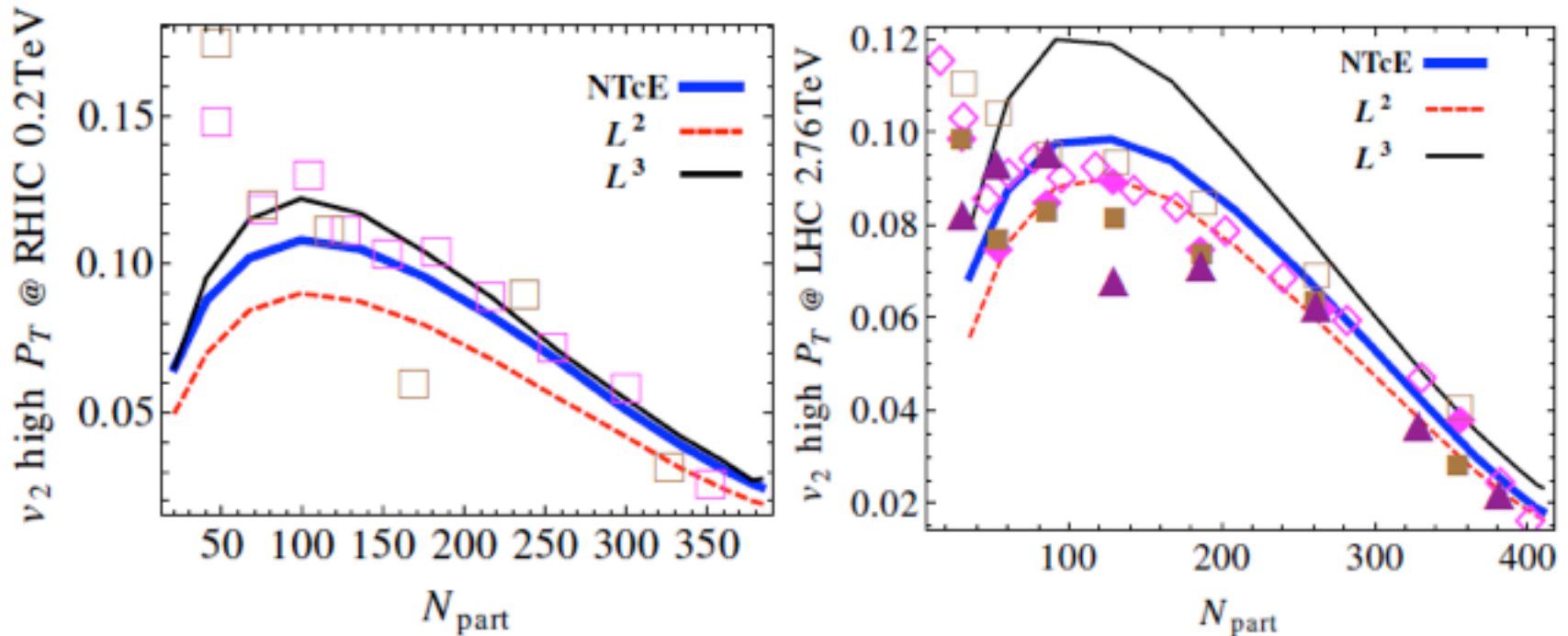
Average jet-medium coupling from RHIC to LHC:
reduced by $\sim 30\%$

$$\langle \kappa[s(l)] \rangle_P = \frac{\int_P \kappa[s(l)] s(l) l dl}{\int_P s(l) l dl}$$

$$\langle \kappa \rangle_{\text{RHIC}} : \langle \kappa \rangle_{\text{LHC}} \approx 1 : 0.72$$

Zhang & JL, arXiv: 1311.5463; 1210.1245

V2 from RHIC to LHC



RED: L^2 model+waterfall

BLUE: L^2 +volcano

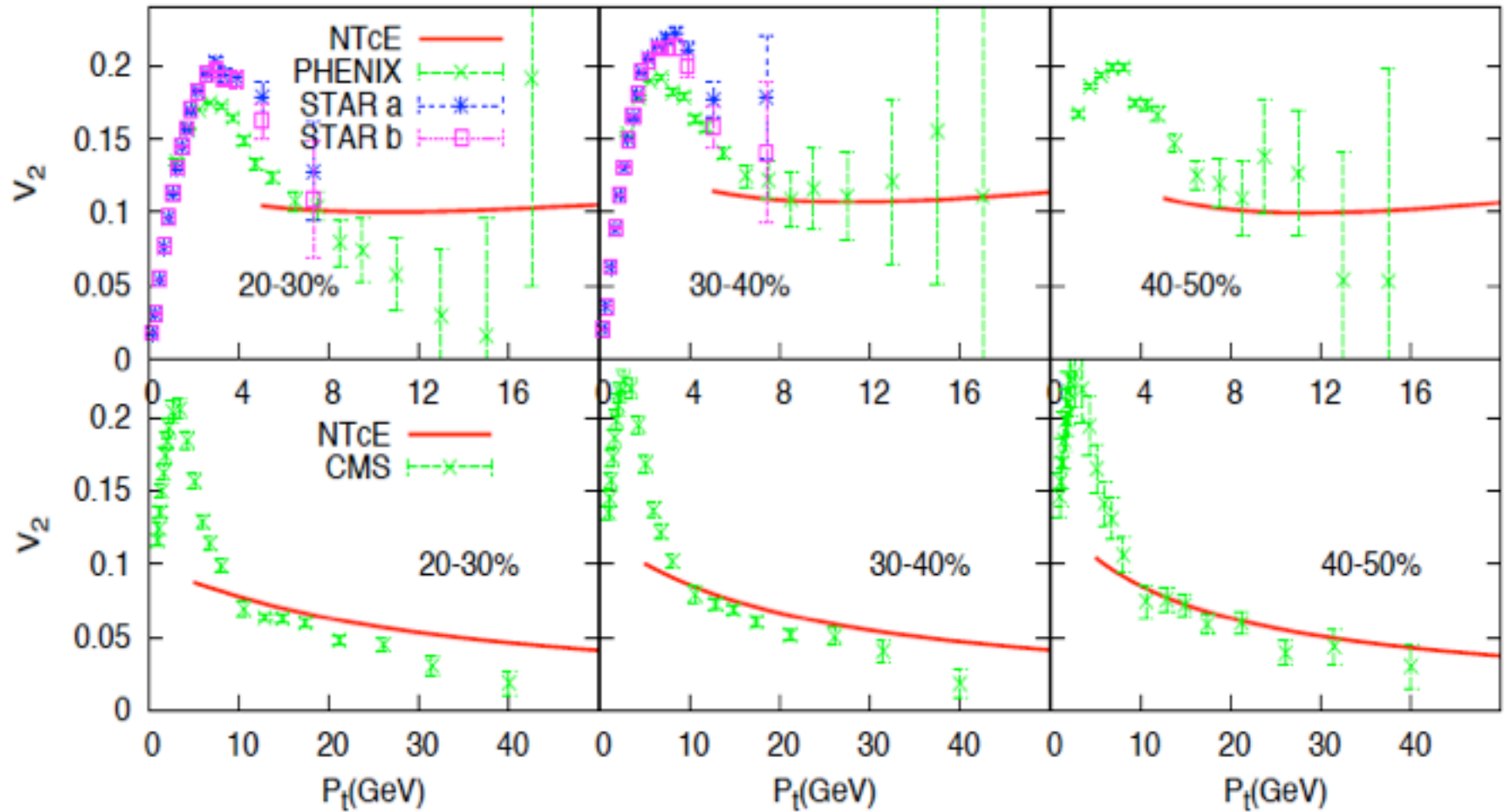
BLACK: L^3 +waterfall

* We do see big difference between waterfall/volcano at RHIC, and this difference becomes much smaller at LHC

* RHIC + LHC data are in favor of the L^2 + Volcano scenario

Zhang & JL, arXiv: 1208.6361

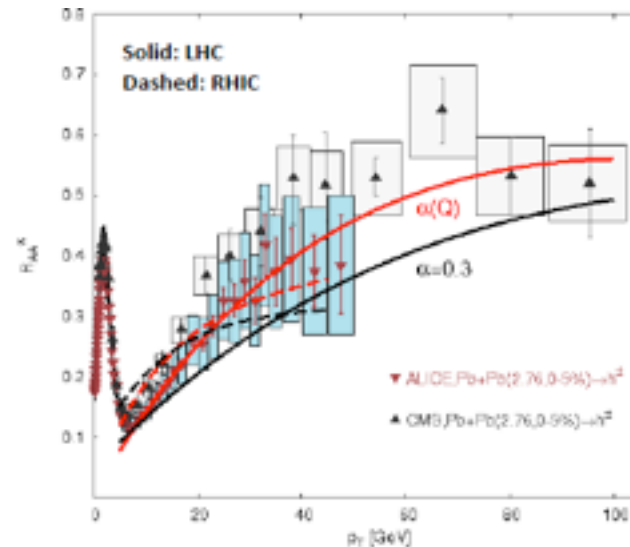
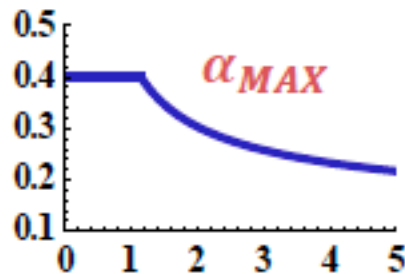
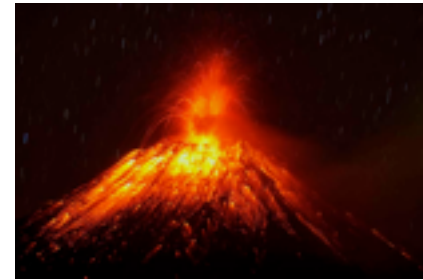
V2 from RHIC to LHC



Zhang & JL, arXiv: 1311.5463

“Volcano” Seen from “Different Angles”

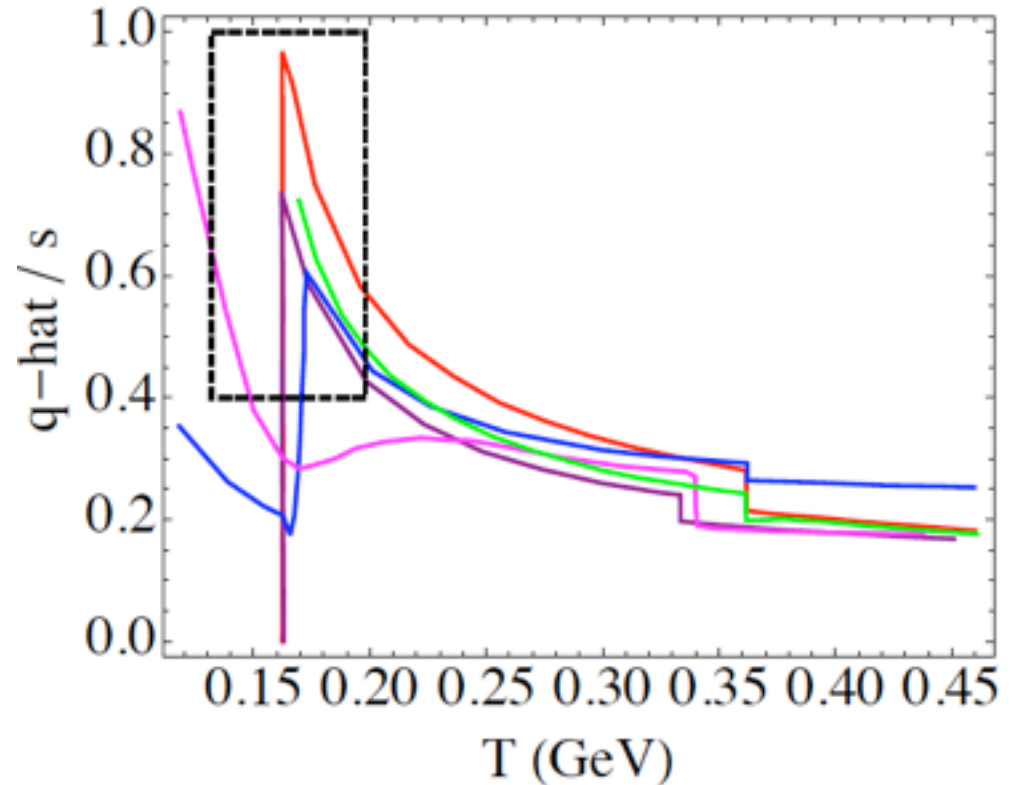
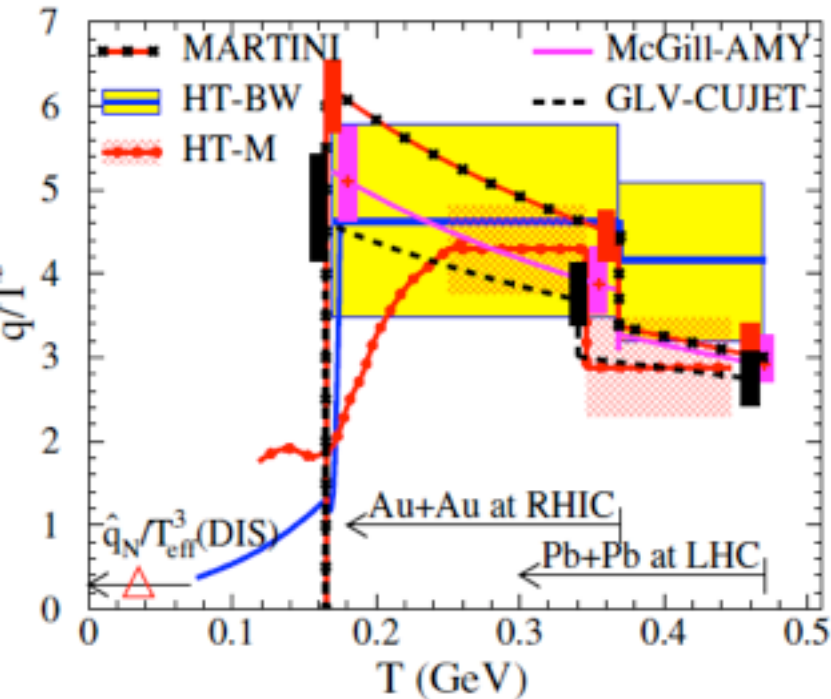
- * Horowitz & Gyulassy:
“surprising transparency” when
simply extrapolating RHIC to LHC
- * Betz & Gyulassy:
10~30% reduction in “polytrope” model
- * Buzzatti & Gyulassy:
Strong running coupling at $T \rightarrow T_c$
(also in Zakharov calculation)



- * Lacey et al, scaling analysis: $q\text{-hat}(\text{LHC}) \sim q\text{-hat}(\text{RHIC})$ despite twice the density
- * Lattice QCD: $Q\text{-bar-Q}$ internal energy shows strong peak at T_c
- * Majumder-Muller-Wang, Dusling-Moore-Teaney:
peak in $q\text{-hat}/\text{density}$ related with dip in η/s ?
- * Majumder: lattice attempt $\rightarrow q\text{-hat}/\text{density}$ showing peak?

Latest Analysis from JET Collaboration

JET Collaboration,
arXiv: 1312.5003



In the paper PRL(2009) we concluded:
“In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near- T_c region than the higher- T QGP phase.”

What are Underlying the “Volcano”?

$T \ll \Lambda_{\text{QCD}}$

$T \sim \Lambda_{\text{QCD}}$

$T \gg \Lambda_{\text{QCD}}$

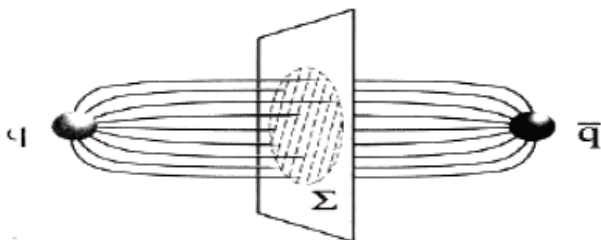
Vacuum: confined

T_c

sQGP

wQGP: screening

T



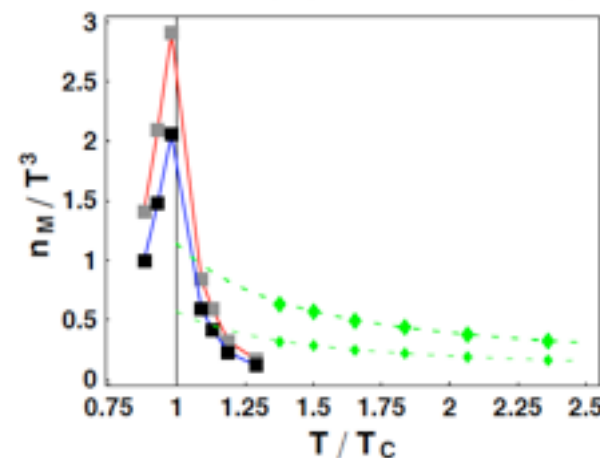
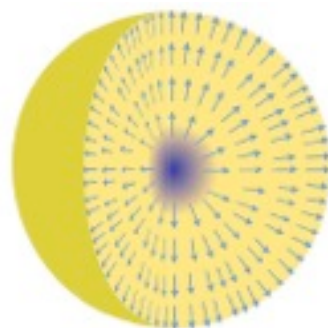
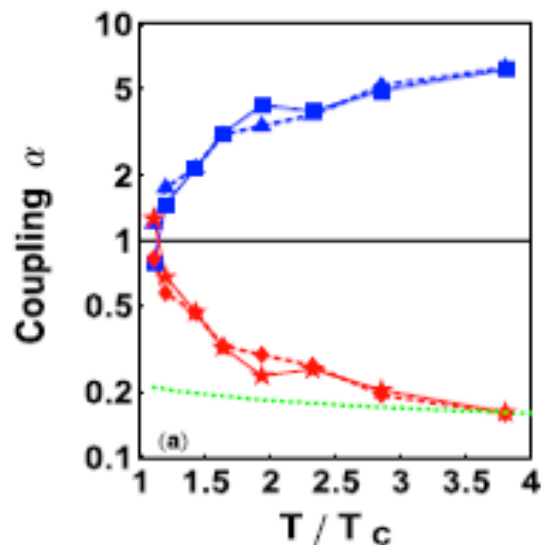
**Emergent plasma
with E & M charges:**
chromo-magnetic monopoles
are the “missing DoF”

Plasma of E-charges
E-screening: $g T$
M-screening: $g^2 T$

Electric Flux Tube:
*Magnetic **Condensate***

$$\alpha_E * \alpha_M = 1.$$

$$\kappa \sim \frac{\alpha_E(T) \alpha_M(T) n_m(T)}{s(T)} = \frac{n_m/T^3}{s/T^3}$$



JL & Shuryak:

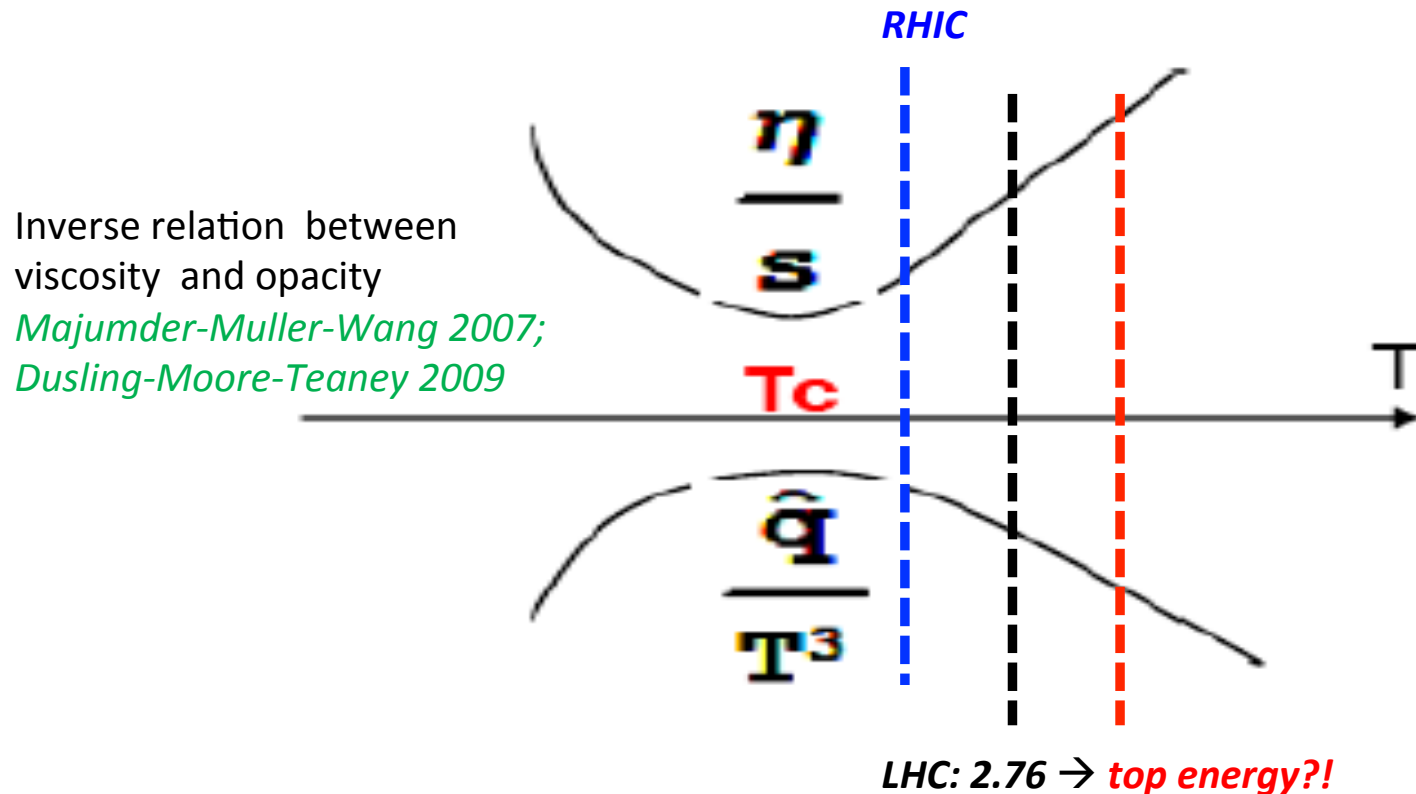
Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008;

Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010;

Phys.Rev.Lett.109:152001,2012.

FROM TALK @ DNP2011

QUENCHING & VISCOSITY LINKED-UP: FROM NEAR T_c TO HIGHER T



Will we see a systematic deviation from RHIC to LHC?

The “see-saw”-QGP expects such a picture to occur in a narrow regime 1-4 T_c .

NEAR-Tc MATTER IS SPECIAL!

* Harmonic flows from RHIC to LHC:

hydro simulations suggest a clear increase of $\sim 40\%$ in η/s

At top RHIC energy, as shown in Fig. 7, the experimental data from STAR [35] and PHENIX [1] is well described when using a constant $\eta/s = 0.12$, which is about 40 % smaller than the value at LHC. A larger effective η/s

Gale, Jeon, Schenke, Tribedy, Venugopalan
arXiv:1209.6330

Also earlier analysis by Frankfurt group and OSU group

* Raa + Geometry + Evolution from RHIC to LHC:

strong evidences for Near-Nc Enhancement

--> predicts a less opaque medium at LHC!

$$\langle \kappa \rangle_{\text{RHIC}} : \langle \kappa \rangle_{\text{LHC}} \approx 1 : 0.72$$

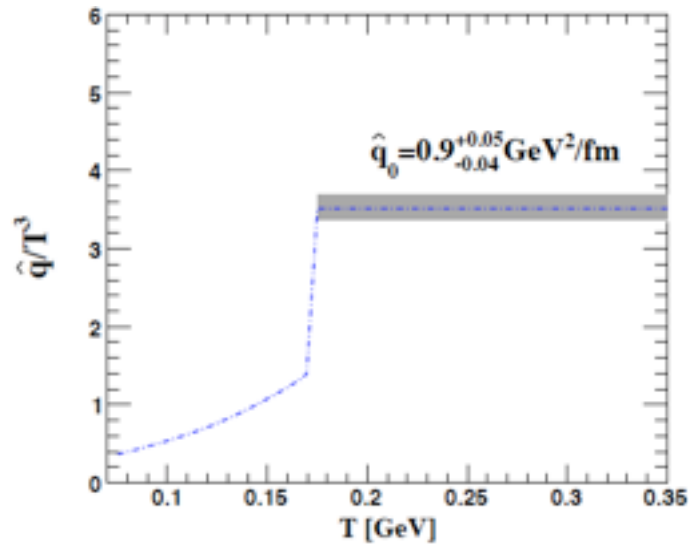
X.Zhang & JL, PLB(2012), arXiv:1208.6361, 1210.1245(PRC2013)

Consistent messages from independent analysis by

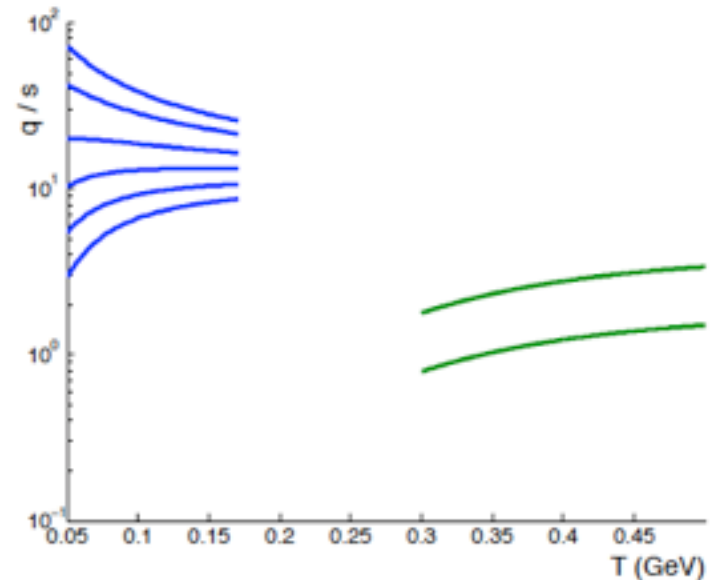
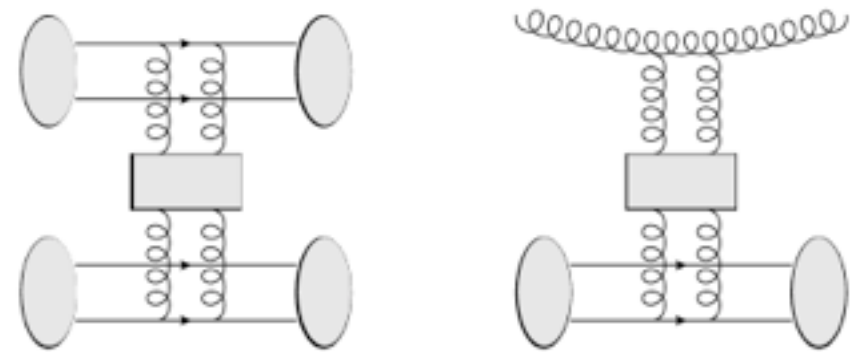
Horowitz & Gyulassy; Betz & Gyulassy; Lacey, et al; B. Zakharov

RHIC+LHC: E-M “See-Saw” Scenario at work
---> anticipating critical test at LHC top energy!

Energy Loss on the Hadronic Side



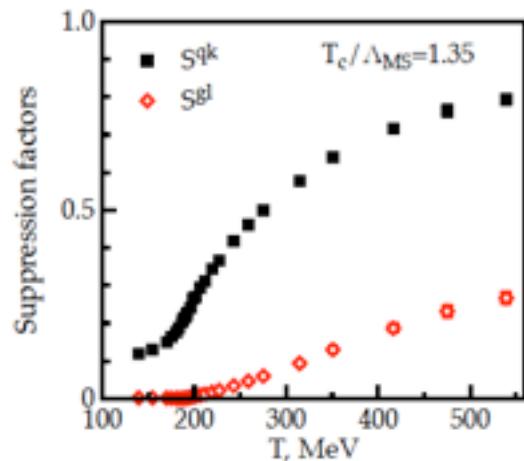
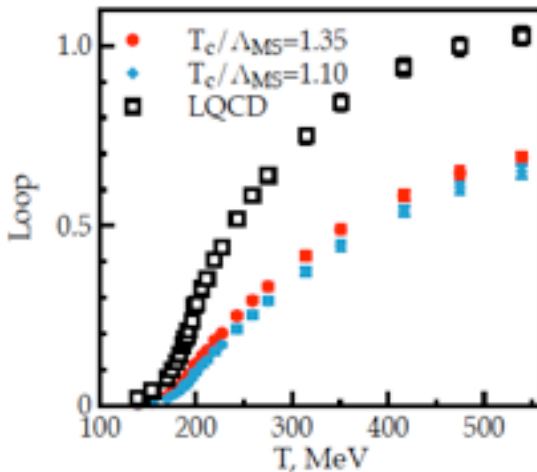
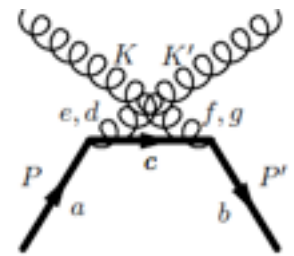
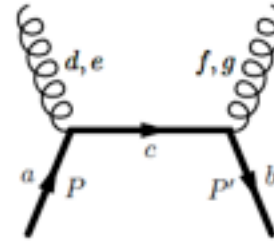
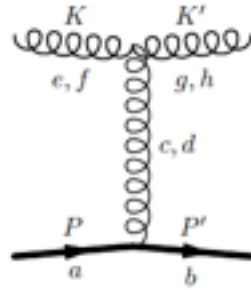
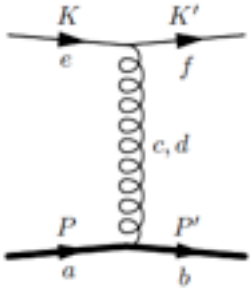
$$\hat{q}_h = \frac{\hat{q}_N}{\rho_N} \left[\frac{2}{3} \sum_M \rho_M(T) + \sum_B \rho_B(T) \right]$$



Chen, Greiner, Wang, Wang, Xu,
arXiv:1002.1165

Hidalgo-Duque, Llanes-Estrada,
arXiv:1309.7211

Energy Loss from the semi-QGP



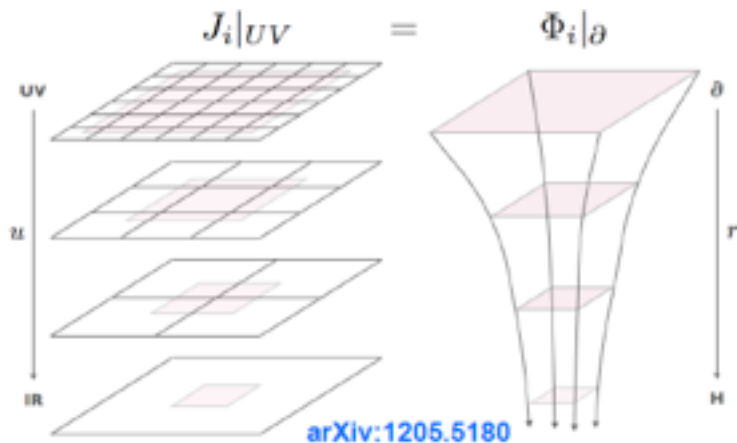
$$S^{\text{qk}}(Q) \sim \ell \quad ; \quad S^{\text{gl}}(Q) \sim \ell^2$$

$$\frac{dE}{dx} = \left(S^{\text{qk}}(Q) \alpha_s^2 T^2 \pi \frac{N_f(N_c^2 - 1)}{12 N_c} \ln \left(\frac{ET}{m_D^2} \right) + S^{\text{gl}}(Q) \left(\frac{(N_c^2 - 1)}{6} \ln \left(\frac{ET}{m_D^2} \right) + \frac{C_f^2}{6} \ln \left(\frac{ET}{M^2} \right) \right) \right)$$

Collisional energy loss of heavy quark in semi-QGP: decrease toward T_c .
(picture from the electric side)
(magnetic charges make the rise.)

Lin, Pisarski, Skokov, arXiv:1312.3340

Going to One More Dimension

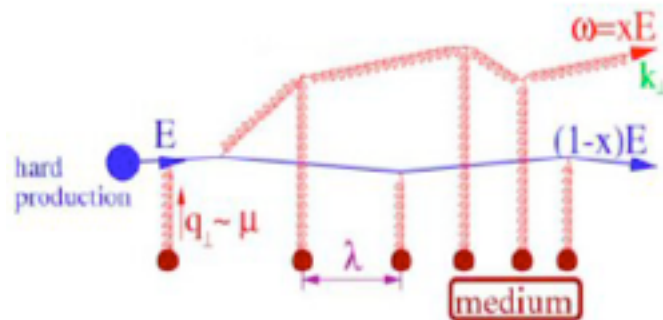


Deforming the conformal-AdS to introduce non-conformal dynamics: using graviton-dilaton system in the bulk

$$S_G = \frac{1}{16\pi G_5} \int d^5x \sqrt{g_s} e^{-2\Phi} (R_s + 4\partial_M \Phi \partial^M \Phi - V_G^s(\Phi))$$

$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2 / \mu_G^2)$$

$$ds_S^2 = e^{2A_s} \left(-f(z) dt^2 + \frac{dz^2}{f(z)} + dx^i dx^i \right)$$

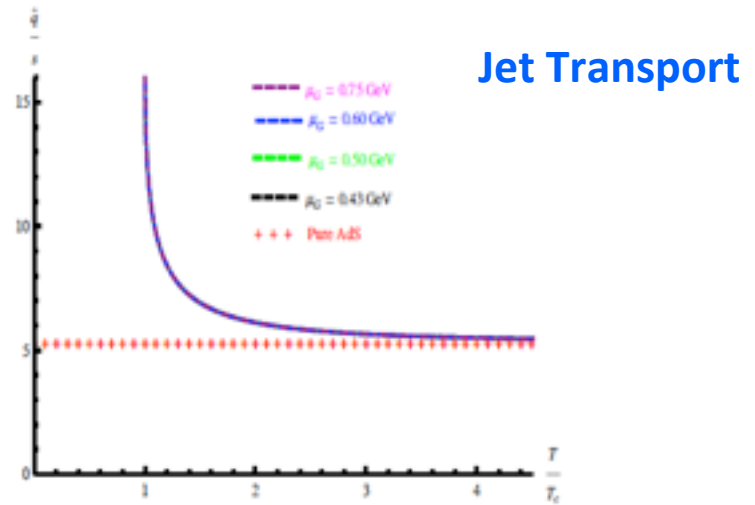
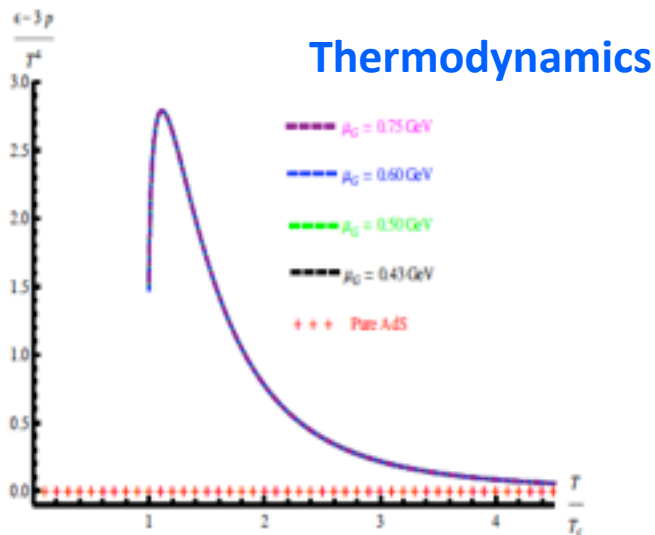


We use the Liu-Rajagopal-Wiedemann scheme to compute \hat{q}

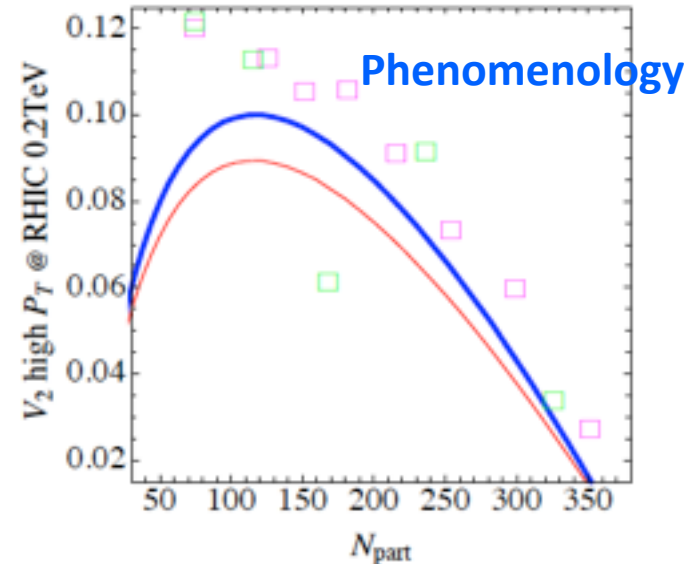
$$\hat{q} = \frac{\sqrt{2}\sqrt{\lambda}}{\pi \int_0^{z_h} dz \sqrt{g_{zz}/(g_{22}g_{--})}},$$

D. Li, JL, M. Huang, arXiv:1401.2035

Results from Non-Conformal Holo-QCD



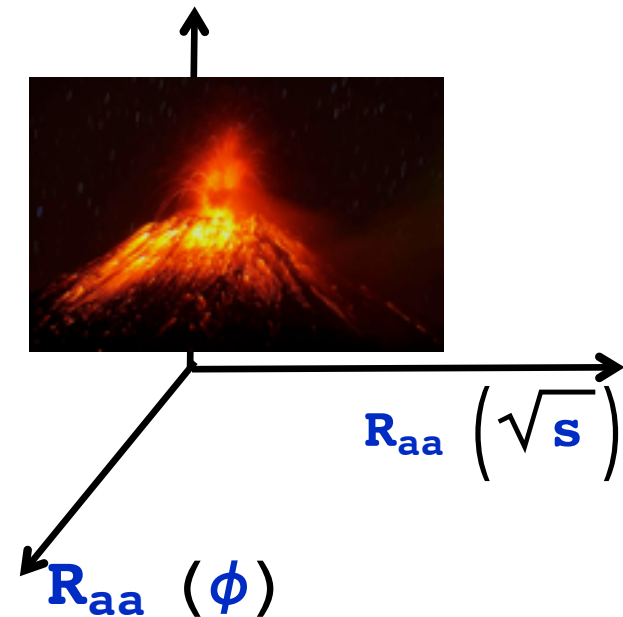
Same non-conformal, non-monotonic, non-perturbative dynamics
---> shows up in trace anomaly and in jet transport parameter
---> considerably increases jet anisotropy toward data as compared with conformal case



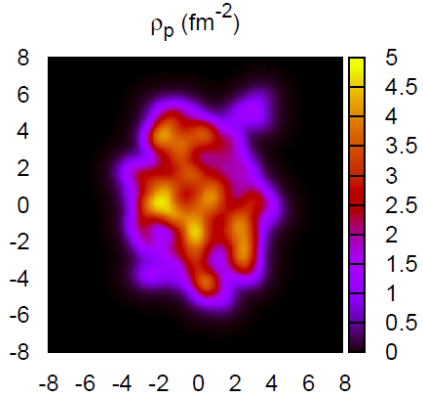
D. Li, JL, M. Huang, arXiv:1401.2035

Summary

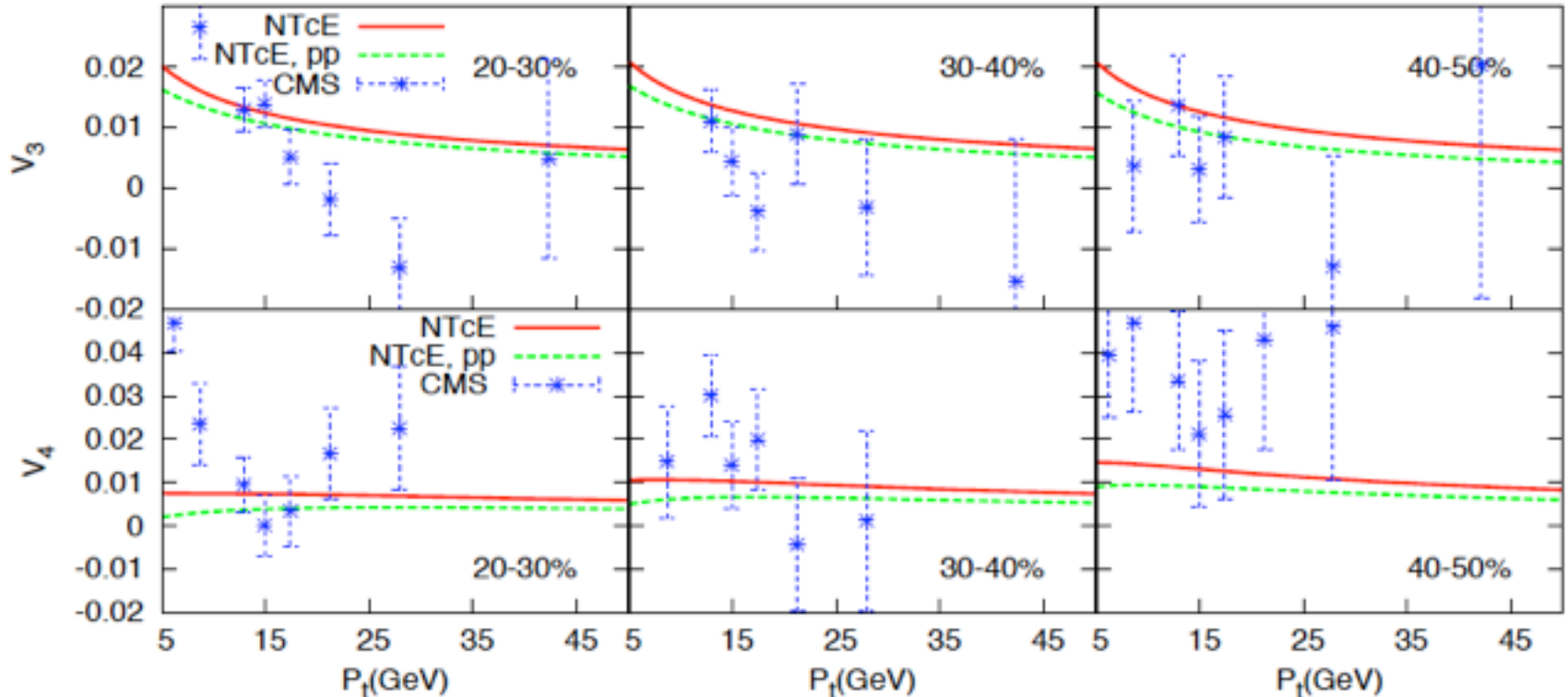
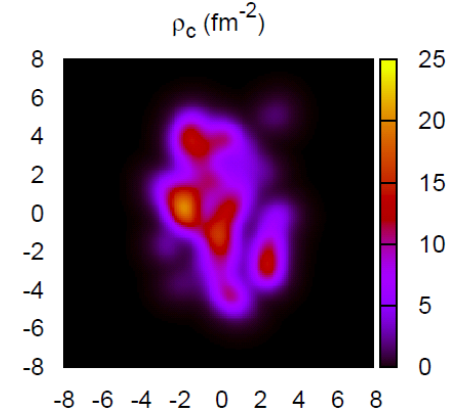
- * An exciting problem: determine and understand the temperature dependence of jet-medium coupling
- * Geometry + Evolution from RHIC to LHC: strong evidences for Near- T_c Enhancement
- * RHIC + LHC together provide unique opportunities for mapping out the detailed shape of the “volcano” and for probing the transition zone between the confined world and the asymptotically free matter.



Hard Probe of Fluctuating Geometry

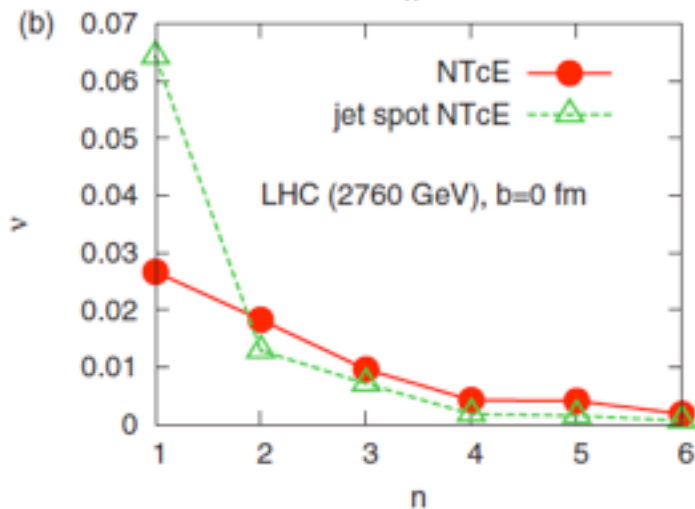
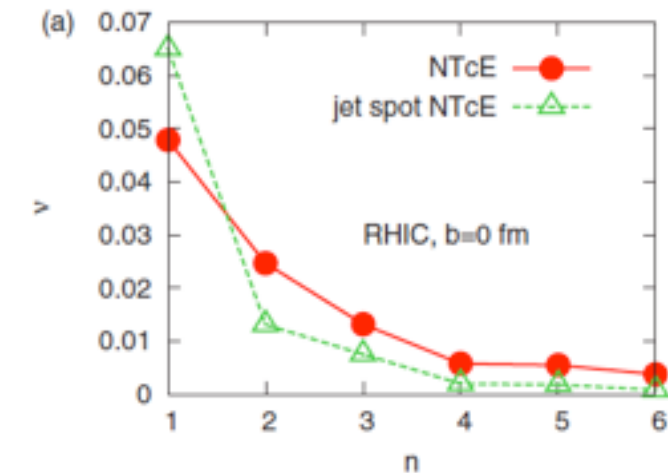


$$R_{AA}(\phi) = R_{AA} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n^J)] \right)$$



X.Zhang & JL, arXiv:1311.5463; 1210.1245; 1202.1047

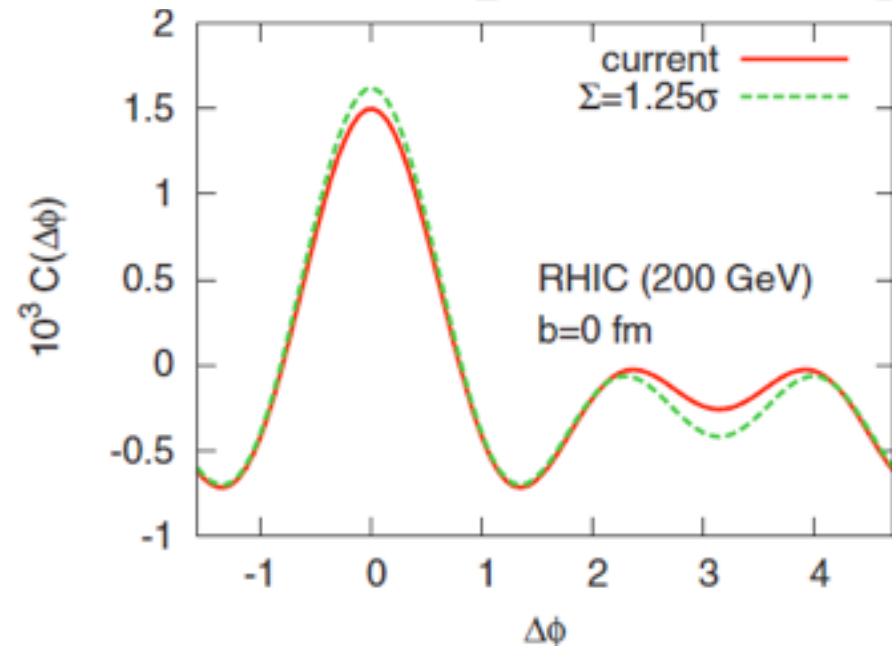
Hard-Soft Di-Hadron Azimuthal Correlations



$$\frac{dN^s}{d\phi^s} \sim 1 + 2 \sum_n v_n^s \cos[n(\phi^s - \psi_n^s)],$$

$$\frac{dN^h}{d\phi^h} \sim 1 + 2 \sum_m v_m^h \cos[m(\phi^h - \psi_m^h)].$$

$$C(\Delta\phi) \equiv 2 \times \left[\sum_n V_{n\Delta} \cos(n\Delta\phi) \right]$$



Both hard and soft sectors “see” and respond to the common fluctuating geometry --> correlations!

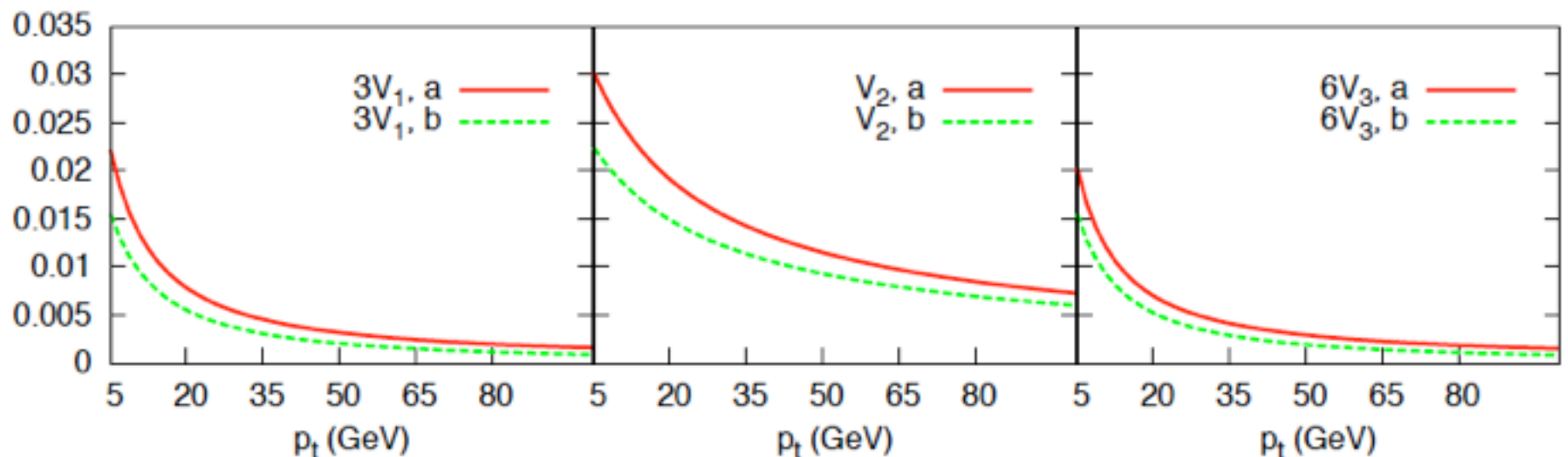
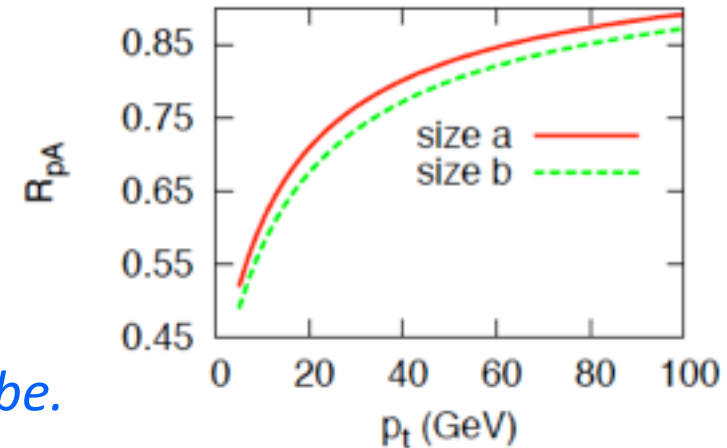
X.Zhang & JL, arXiv:1210.1245; 1202.1047

Final State Attenuation in the Mini-Bang?

High multiplicity pPb collisions at LHC
(and dAu at RHIC) have generated
significant interests recently:

*Are they “Mini-Bangs” creating matter
with significant final state interactions?*

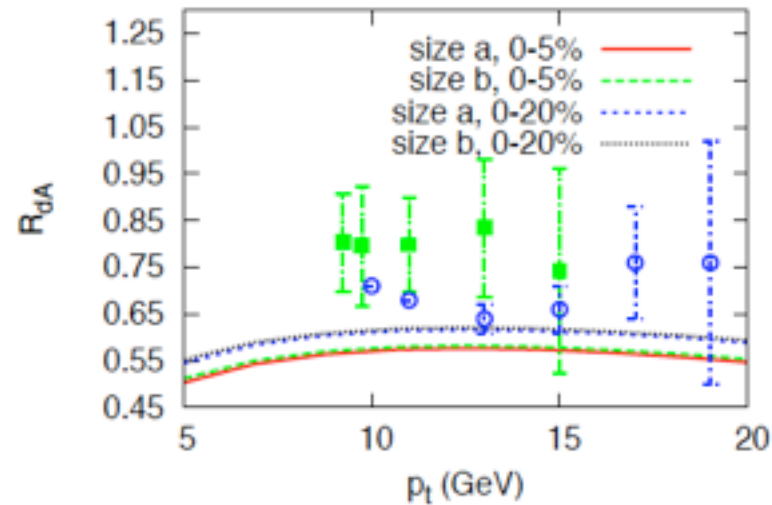
Possible jet attenuation is an independent probe.



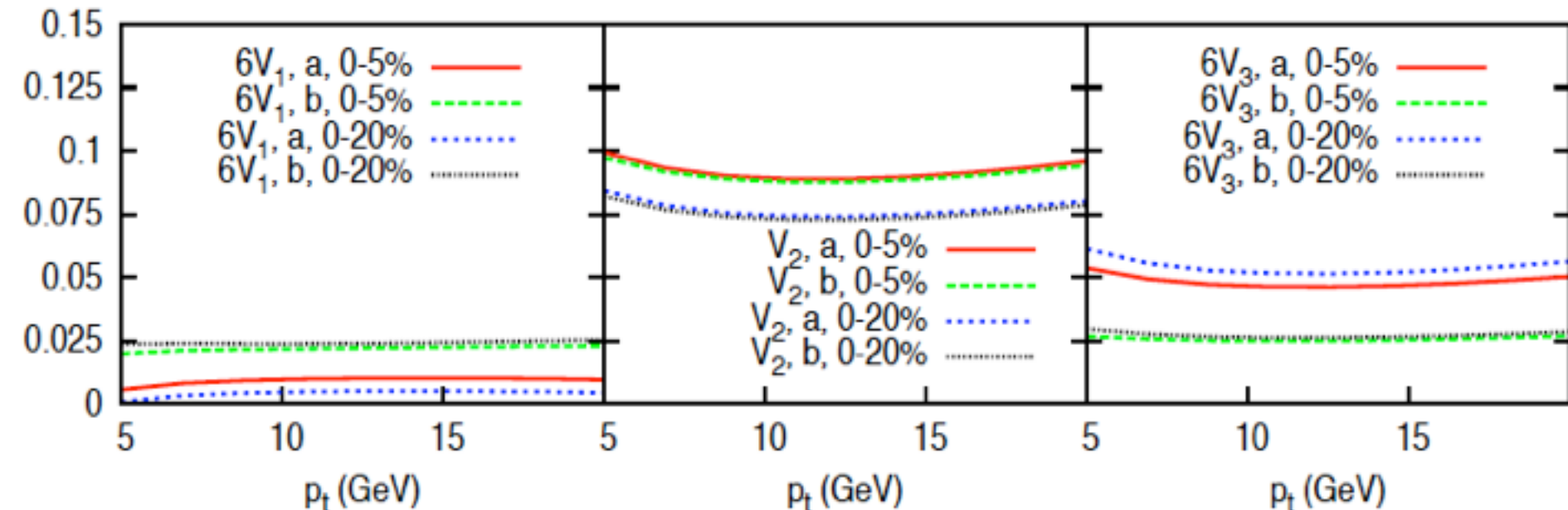
R_{pA} itself could be rather tricky!

High p_t anisotropy, particularly v_2 could be a golden signal!

“Mini-Bangs”: High Multi. dAu at RHIC



High p_t anisotropy,
particularly $v_2 \sim 10\%$
--> could be a golden signal
to tell YES or NO



X.Zhang & J.L, arXiv:1311.5463